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# CCD Technology for LSST

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MIT Lincoln Laboratory



# Outline

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- **Overview**
- **Some properties of current large imagers for astronomy**
  - **Noise**
  - **Back illumination**
  - **PSF**
- **Other technologies of potential interest to LSST**
  - **Anti-blooming**
  - **Electronic shutter**
  - **Deep depletion**
  - **Orthogonal-transfer CCD and OTA**
- **Summary**



# Lincoln Microelectronics Laboratory



- Megapixel CCD imagers (x-ray, UV, IR)
- Avalanche photodiode arrays
- 0.25- $\mu\text{m}$  mixed-signal FDSOI CMOS
- 0.18- $\mu\text{m}$  low-power FDSOI CMOS
- Sub-100-nm FDSOI CMOS (under development)
- Integrated 0.35- $\mu\text{m}$ , 3.3-V CCD/SOI CMOS
- 3-D circuit stacking
- Nb-based superconducting circuits
- MEMS RF switches and mirrors

- 8100 ft<sup>2</sup> class 10, 10,000 ft<sup>2</sup> class 100; 70,000 ft<sup>2</sup> total
- Production-class 0.25- $\mu\text{m}$  CMOS toolset
  - Angled ion implantation
  - Rapid thermal processing
  - Cluster metallization and dry etch
  - Chem-mechanical planarization
- Advanced lithography capabilities
  - I-Line, 248 nm, 193 nm, and 157 nm
  - 5-nm spot size e-beam lithography





# CCD Imagers

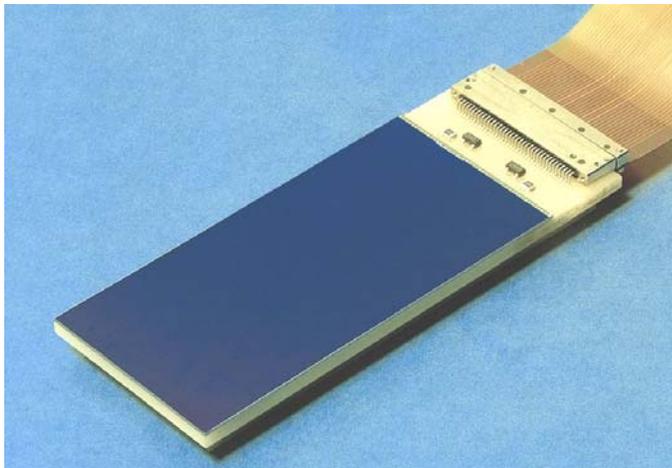
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- **Process**
  - Triple-poly, n-buried channel
  - High-resistivity Si for deep depletion
  - Back-illuminated processing with full-wafer thinning
  - 150-mm wafers
- **Recent astronomy-related devices**
  - 2K × 4K pixels, 15×15- $\mu\text{m}$  pixels
  - 3K × 6K pixels, 10×10- $\mu\text{m}$  pixels
  - 2K × 4K OTCCD, 15×15- $\mu\text{m}$  pixels
  - Misc. small imagers for adaptive optics (e.g. 128×128, 8 ports)
- **Other**
  - Burst-mode imager
  - Exploratory devices (merged CCD/CMOS)
  - Curved CCDs

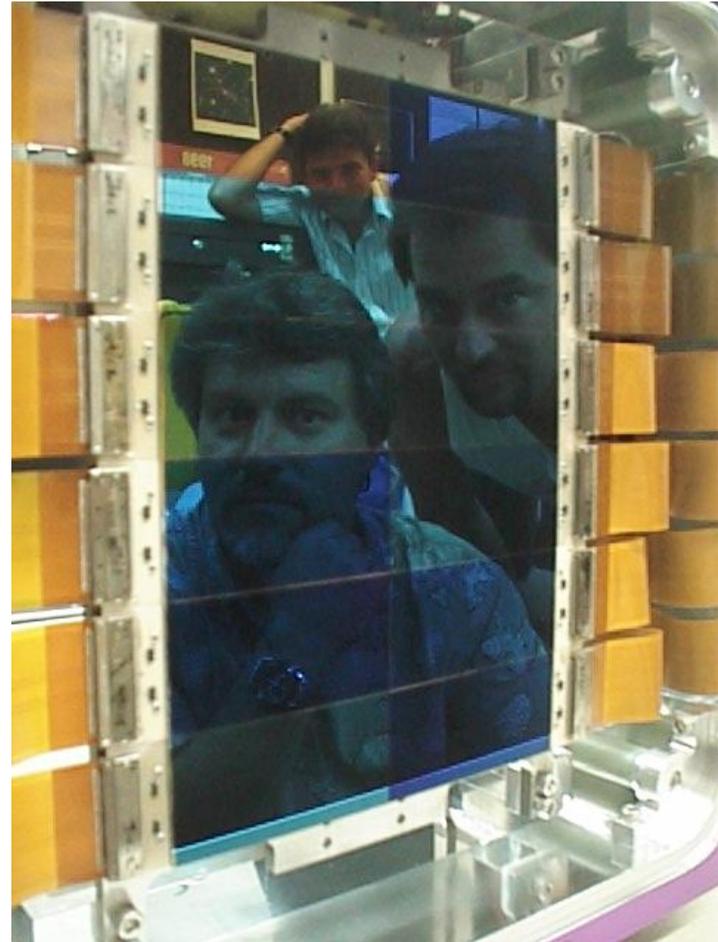


# Large CCD Focal Plane for Astronomy

- **Collaboration with consortium of astronomers**
  - **2k×4k back-illuminated CCD**
  - **Two output ports**
  - **15×15- $\mu\text{m}$  pixels**
  - **Three-side abutable**



**2k×4k imager**



**Canada-France-Hawaii telescope  
focal plane: 12 CCDs, 100 Mpixels**



# Outline

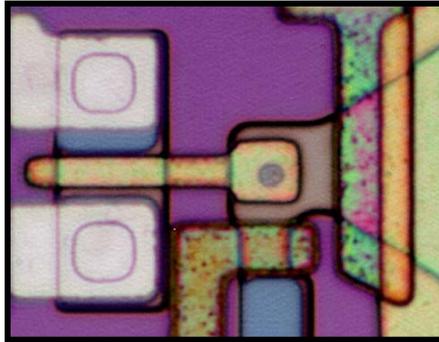
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  - **Orthogonal-transfer CCD and OTA**
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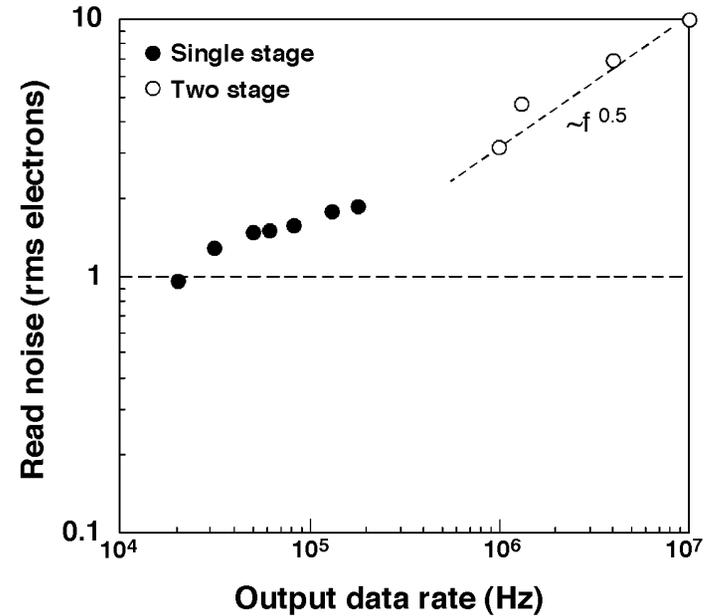
# CCD Noise

## Charge-Sensing Amplifier



Sense-node capacitance ~5 fF  
(20  $\mu\text{V}/e^-$ )

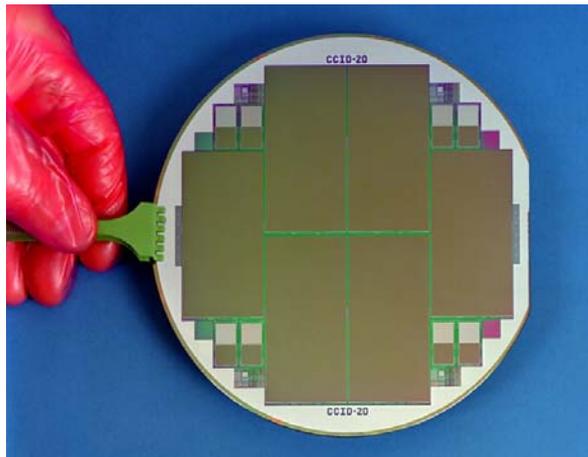
## Best measured read noise vs data rate



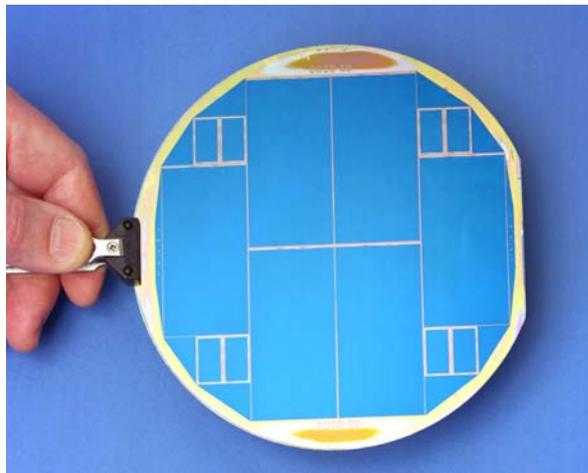
- Multiple readout ports to lower readout noise
  - Noise reduced approximately as square root of bandwidth
  - Port-to-port non-uniformity
  - Additional support circuitry



# Back-Illumination Process

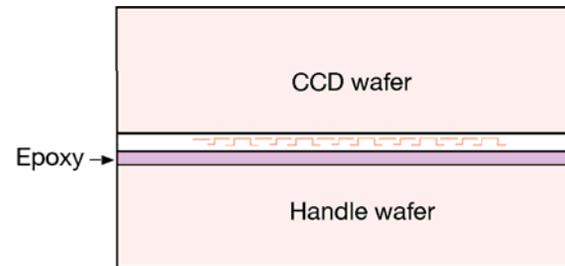


CCD wafer, pre-thinning

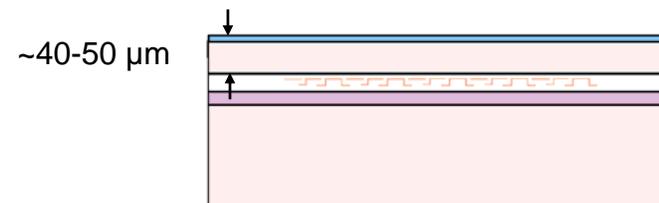


After backside processing

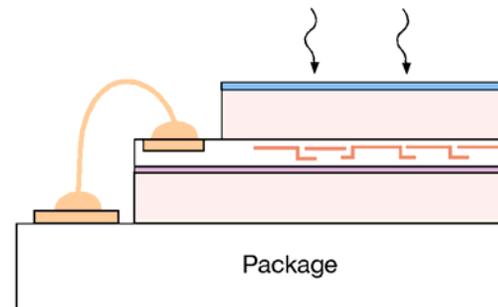
## Process flow



Bond CCD wafer to handle wafer



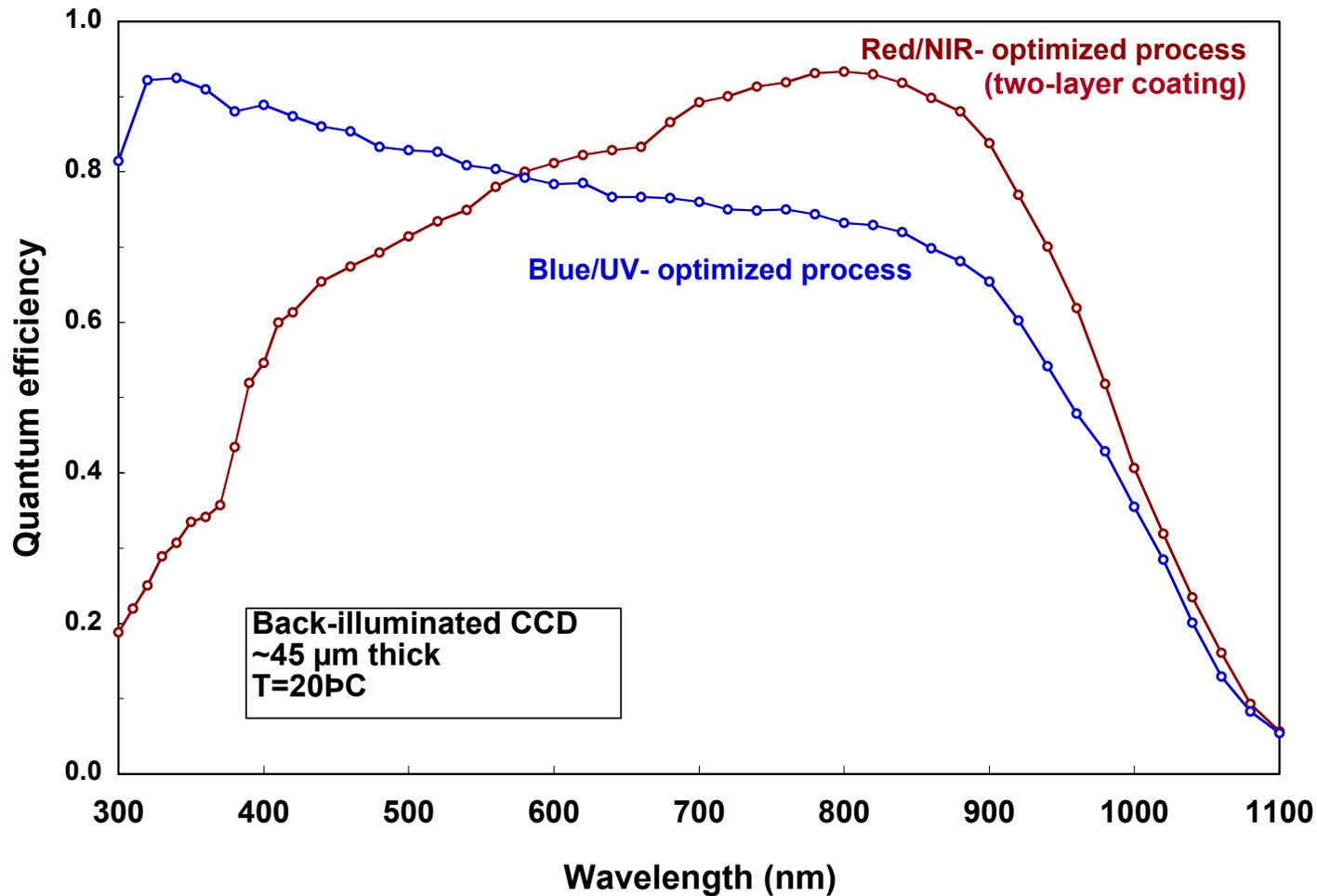
Chemically thin CCD wafer, apply back-surface treatment, and anti-reflection coating



Etch "streets" and bond-pad vias around device perimeter, saw, and package



# Quantum Efficiency of Back-Illuminated CCDs



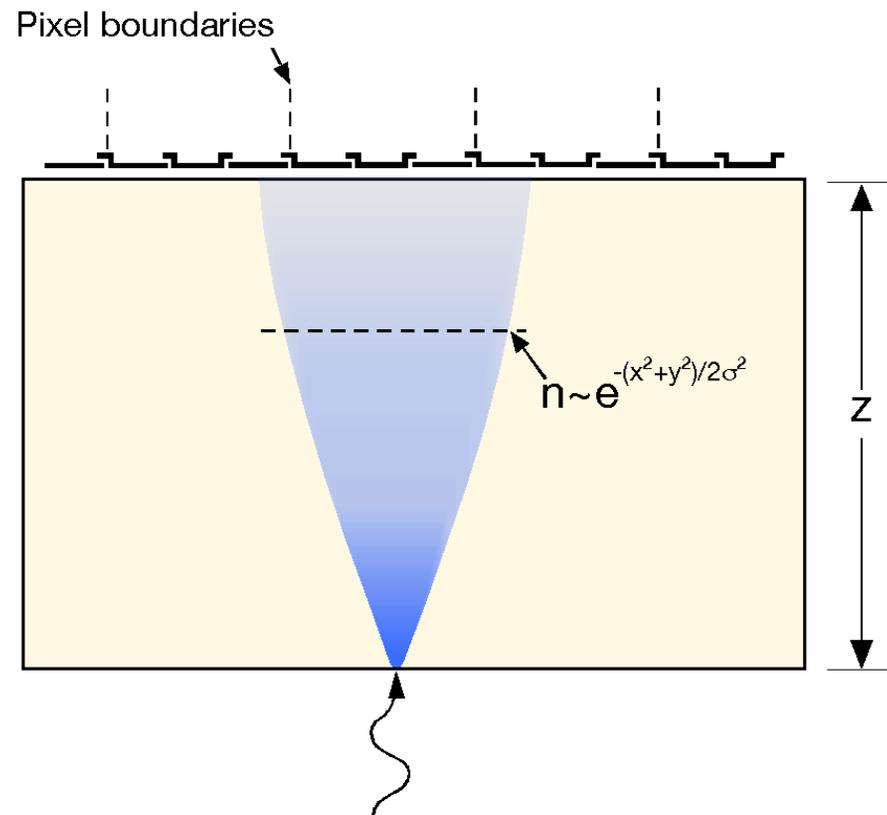


# Charge Spreading (Charge PSF)

- Spreading of charge due to thermal diffusion
- Minimized by thin devices, strong vertical drift fields
- Charge spread given by

$$\sigma \cong z \left( \frac{2kT/q}{V_{fb}} \right)^{0.5}$$

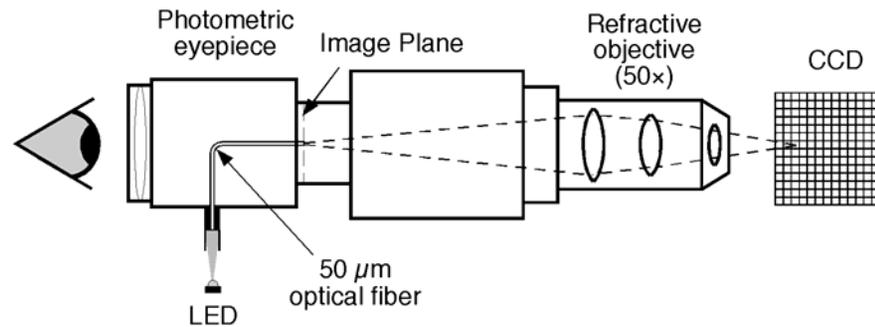
where  $V_{fb}$  = front-back voltage





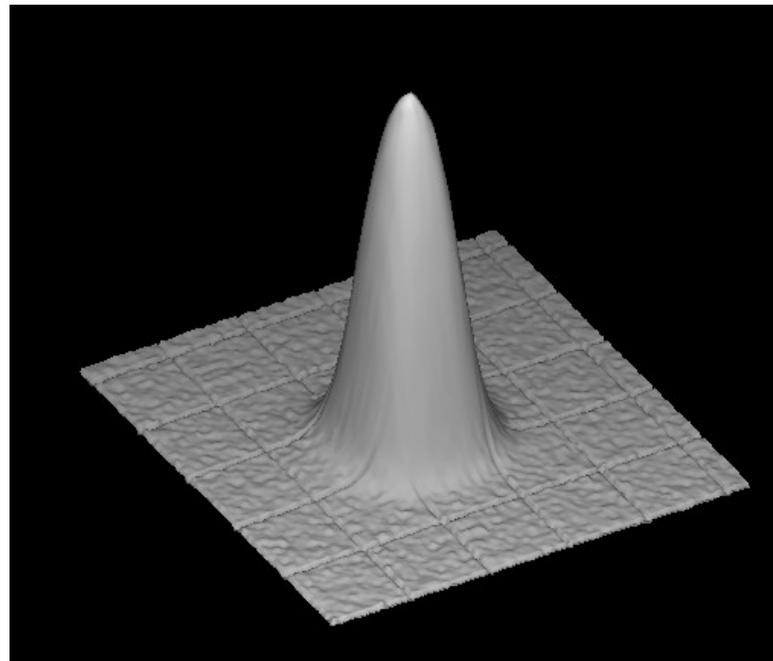
# Device Response to Scanned Light Spot

## Measurement system



## Measured 2D scan

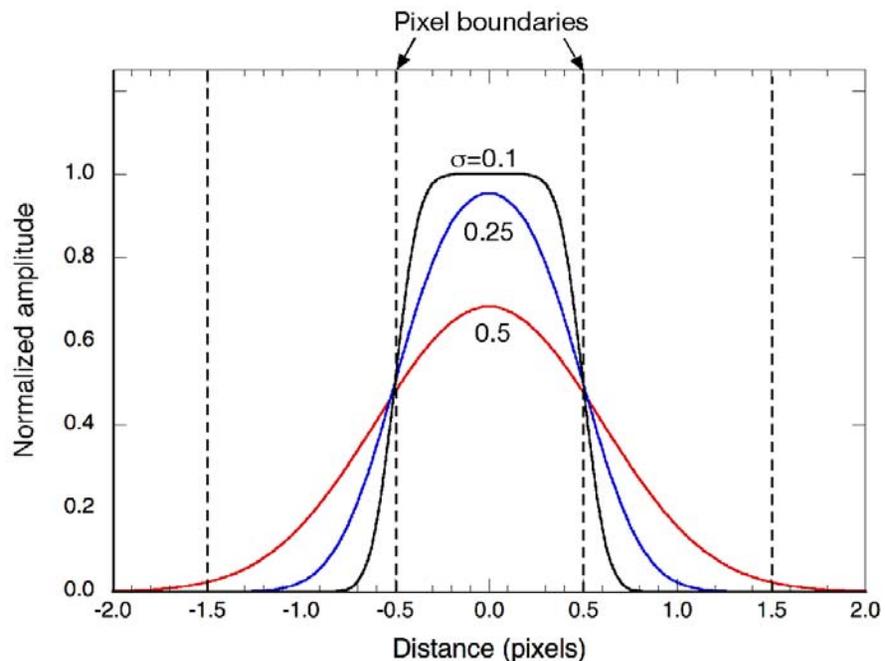
- 15×15-μm pixel (pixel boundaries superimposed on data)
- $\lambda=430$  nm



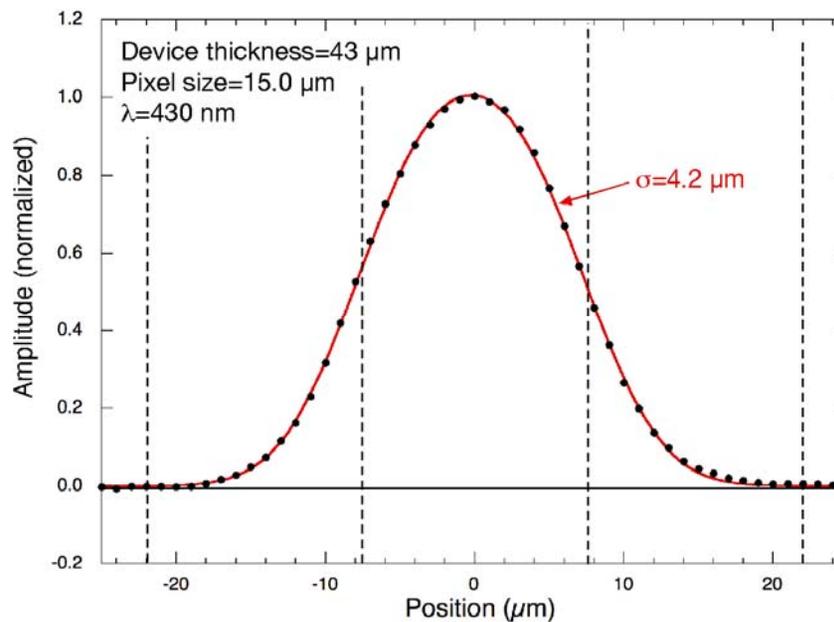


# Measurement of Charge-Cloud Size

## 1D optical spot scan through pixel centers



**Calculated**  
(dimensions normalized  
to pixel size)



**Measured data and  
calculated fit**



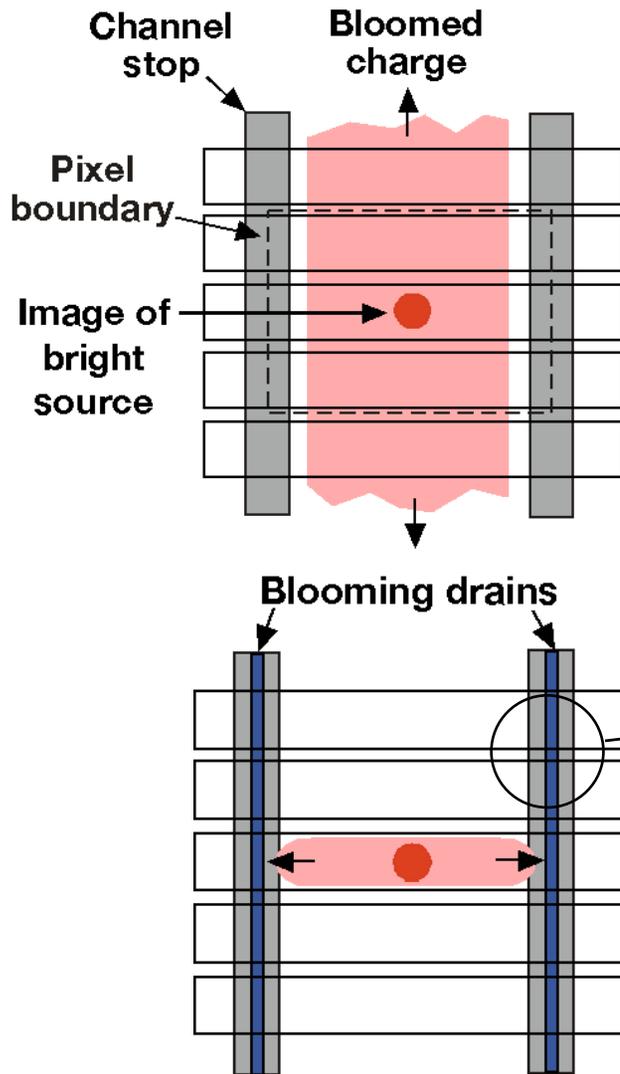
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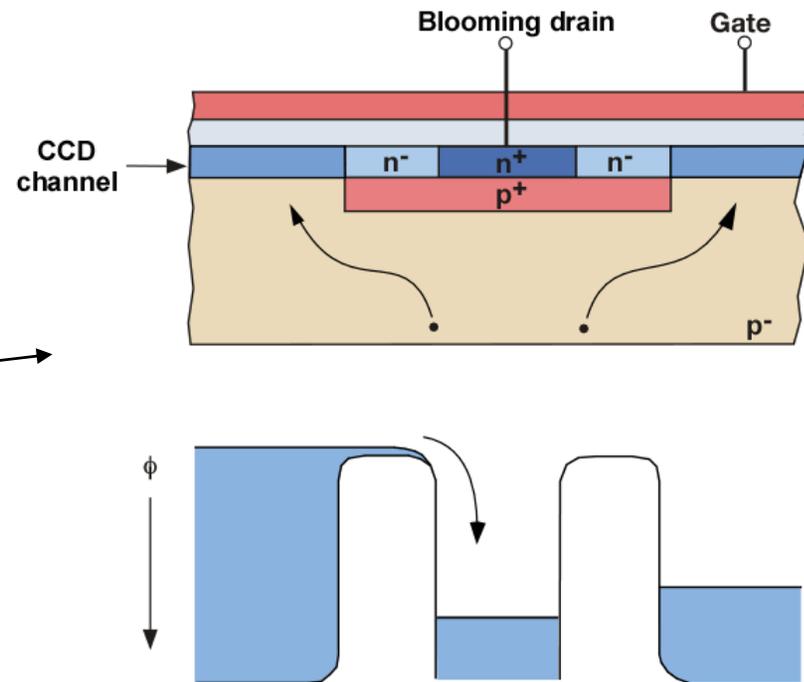
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# Blooming Control



- Straightforward addition to CCD process (one extra photomask)
- Compact ( $< 3 \mu\text{m}$  wide)
- Little impact on device yield





# Blooming Control Test

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1000× optical overload



**Blooming control disabled**

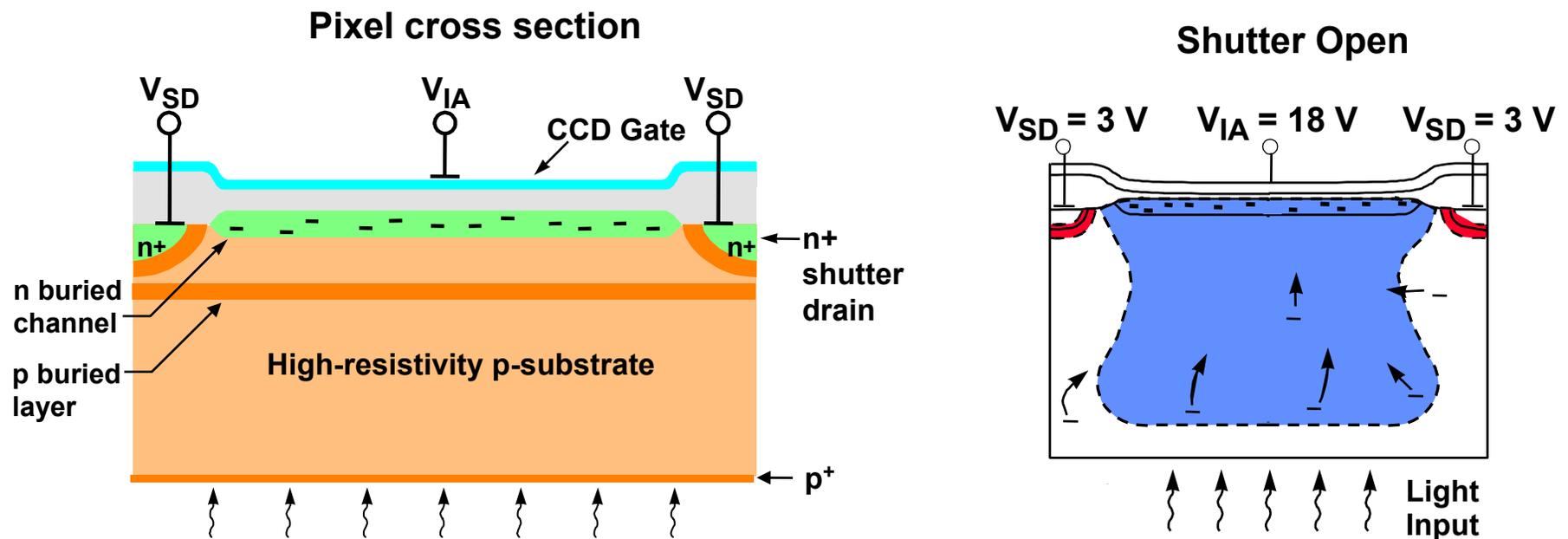


**Blooming control enabled**



# Integrated Electronic Shutter for Back-Illuminated CCD Imager

- Short adjustable exposure times (10 - 100 ns)
- High extinction ratios ( $> 5000$  for  $\lambda < 580$  nm)
- Sensitive (100 % fill factor, high quantum efficiency)

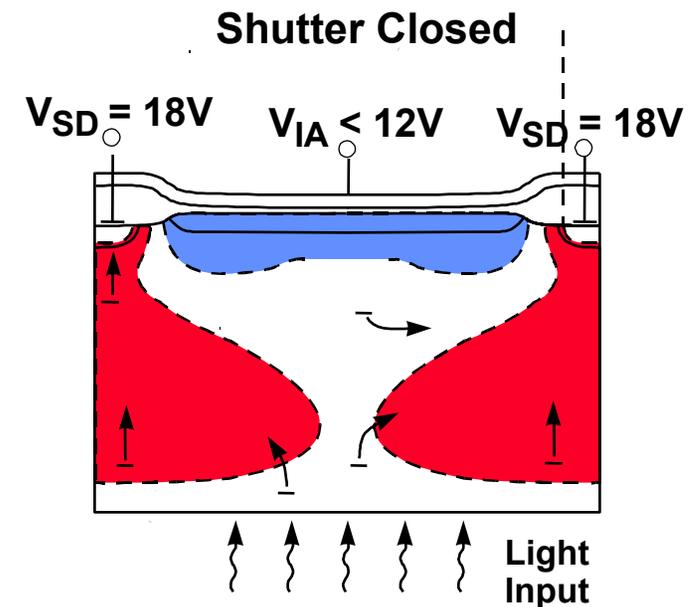
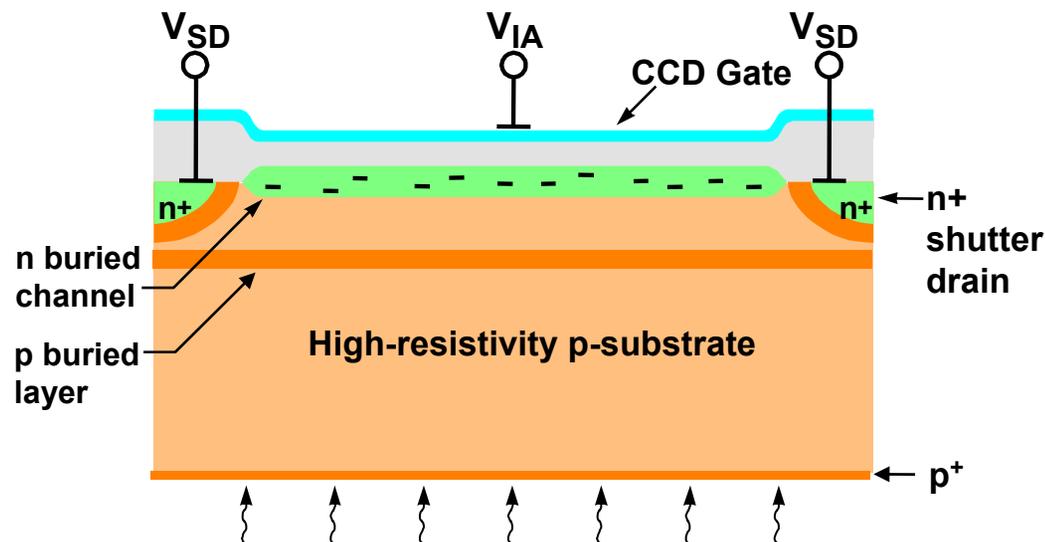




# Integrated Electronic Shutter for Back-Illuminated CCD Imager

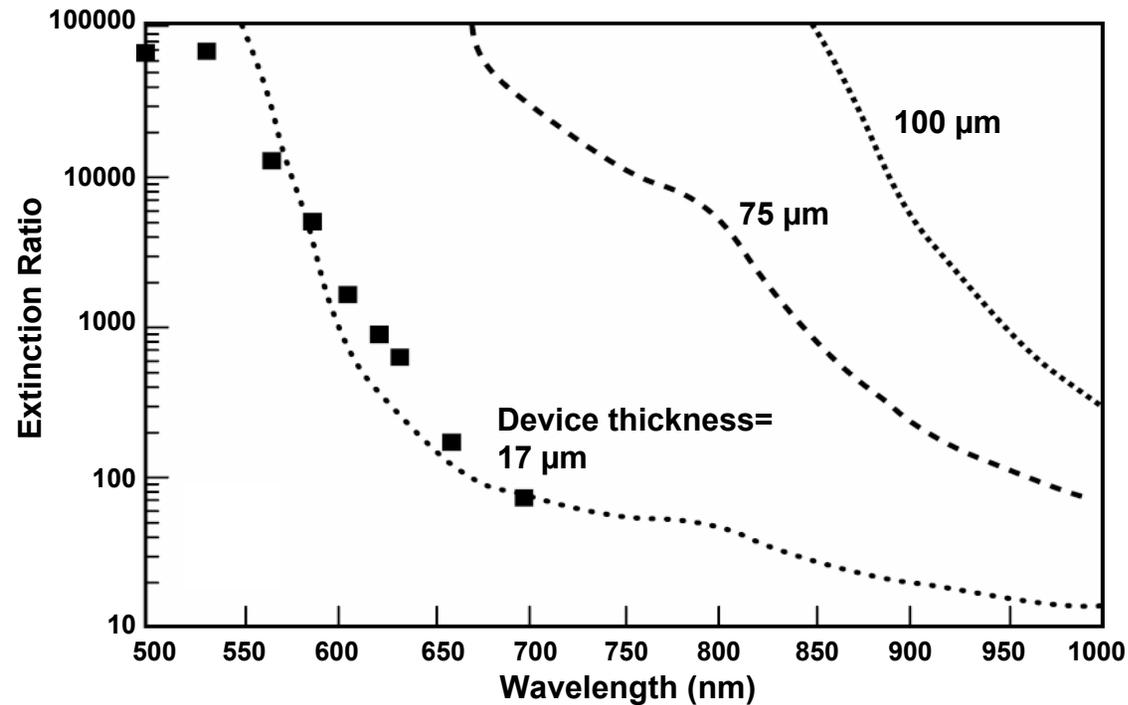
- Short adjustable exposure times (10 – 100 ns)
- High extinction ratios ( $> 5000$  for  $\lambda < 580$  nm)
- Sensitive (100 % fill factor, high quantum efficiency)

Electronic Shutter Pixel Cross Section





# Extinction Ratio

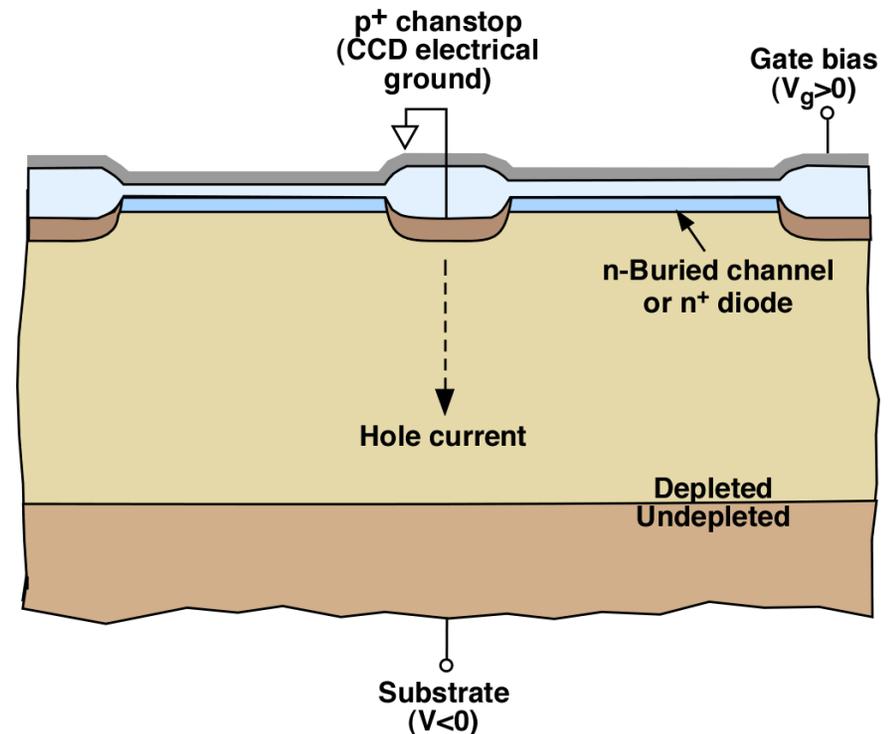


- Extinction ratio: photons collected shutter open to those collected shutter closed
- Increasing absorption lengths with wavelength decreases extinction ratio
- Increasing thickness improves extinction
  - Biases must be increased to maintain interpixel response



# Enhanced Depletion Depth and Substrate Drift Fields

- Traditional approach to deep depletion on MOS CCDs:
  - High resistivity substrate
  - High gate biases
- Substrate bias
  - Enhances depletion-layer drift field for reduced carrier PSF
  - Enables thicker, fully depleted sensor
  - Requires narrow chanstops to suppress parasitic hole current

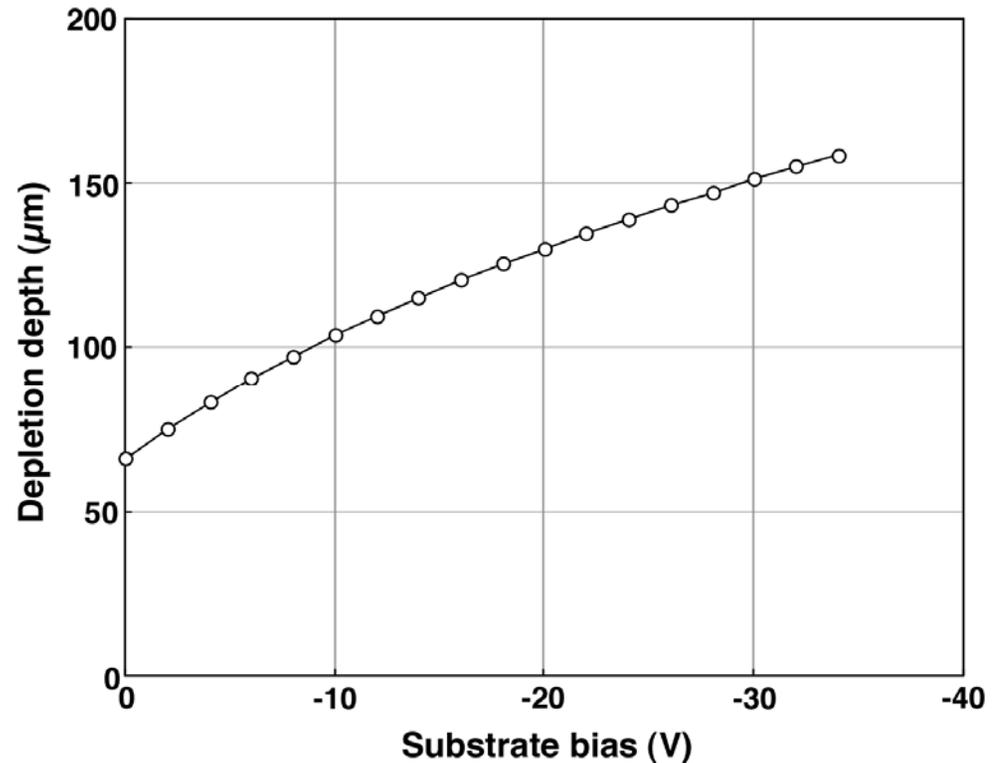


CCD cross section



# Tests of Prototype Deep-Depletion CCD

- Device made on 6300- $\Omega$ -cm p-type FZ material
- Depletion depth improvement
  - 65  $\mu\text{m}$  at normal gate biases and  $V_{\text{SUB}}=0$
  - 160  $\mu\text{m}$  at  $V_{\text{SUB}}= -35 \text{ V}$

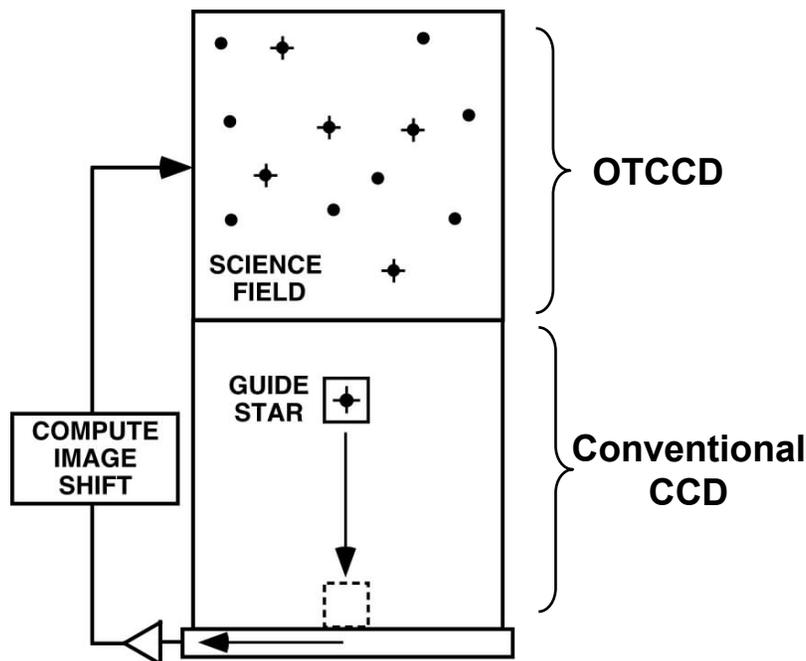


Depletion depth vs.  
substrate bias  
( $N_A=2.2\times 10^{12} \text{ cm}^{-3}$ )

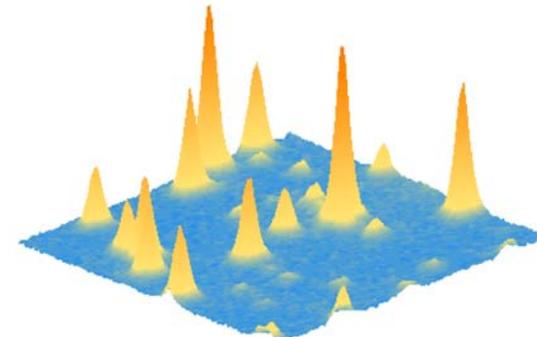


# Orthogonal-Transfer CCD (OTCCD)

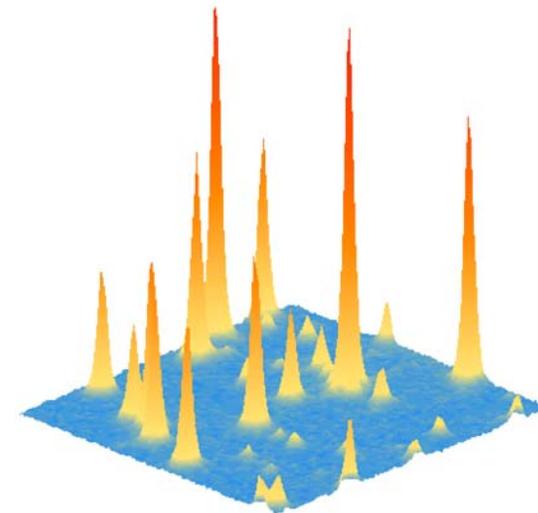
- Enables charge transfer in arbitrary directions
- Can remove blurring due to scene or platform motion
  - Demonstrated for tip/tilt correction in astronomy
  - May be used for imaging from unstable platforms (e.g., satellites)



## Star-cluster imagery



No Motion Compensation

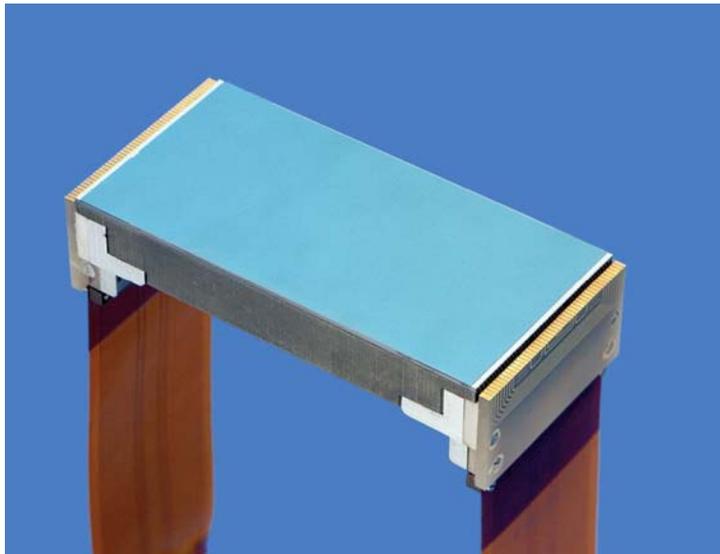


With Motion Compensation

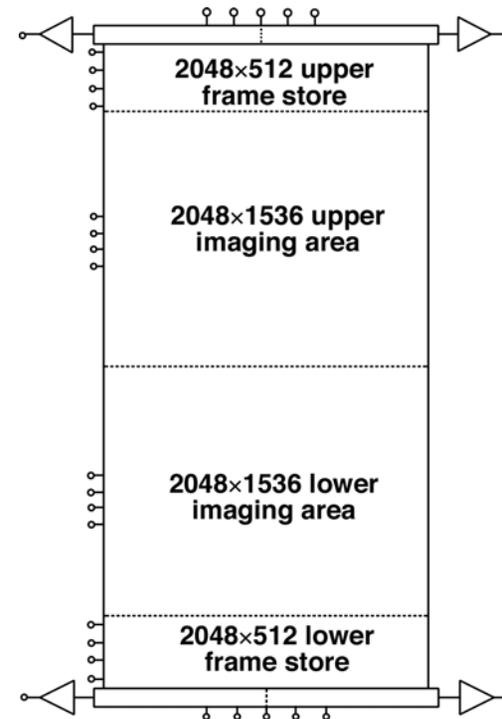


# Large-Format OTCCD

- **2K × 4K pixels, 15 × 15 μm**
- **31 × 62-cm die**
- **Four-side abutable device and package for focal-plane arrays**



**Packaged back-illuminated device**

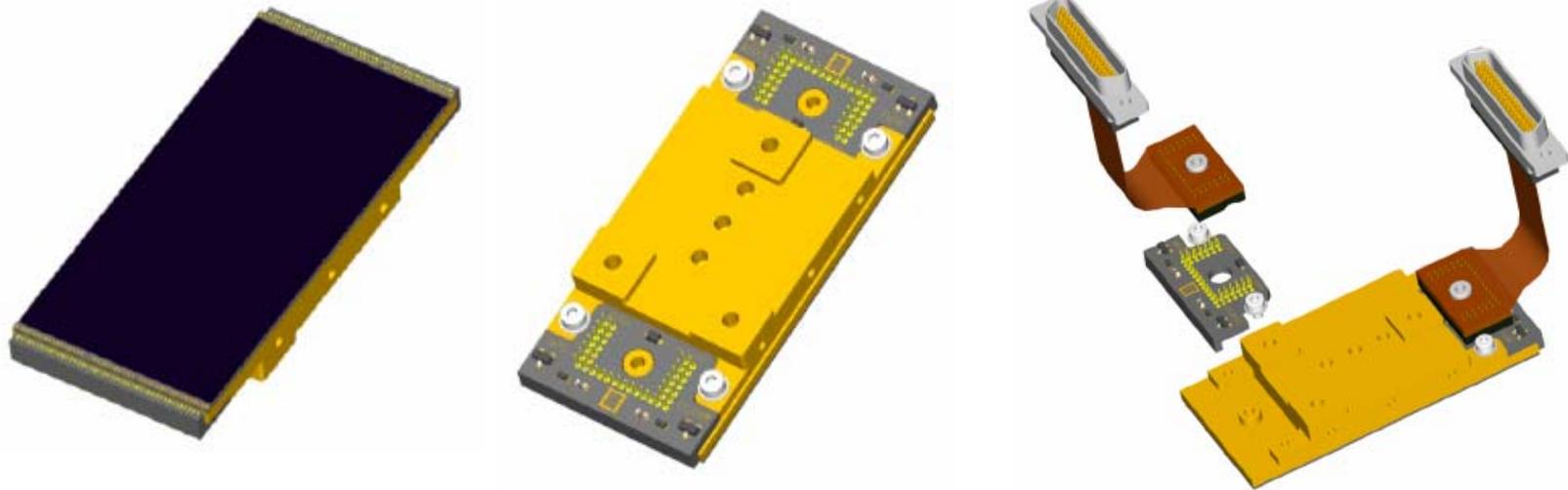


**Device schematic**



# Improved Package for Large OTCCD (in fabrication)

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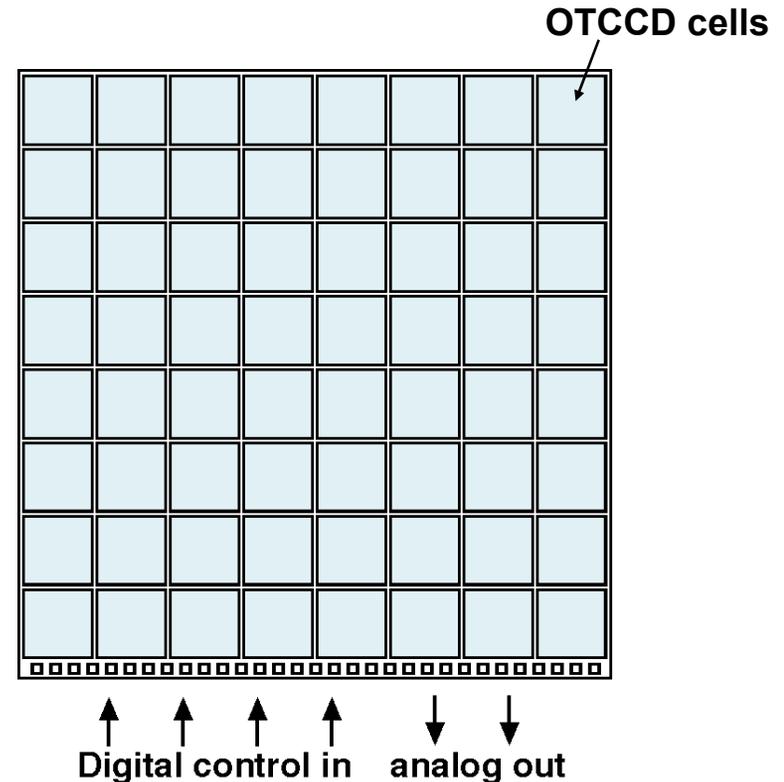


Design by G. Luppino



# Orthogonal Transfer Array (OTA)

- **8×8 array of small OTCCDs , each  $\sim 500 \times 500$  pixels**
- **OTCCD cells independently clocked via on-chip control logic**
- **Cells read out one row at a time at 1-MHz read rate; readout time  $\sim 2$  s**
- **Subset of cells (typically five) selectable for tracking guidestars at  $\sim 30$ -Hz rates**

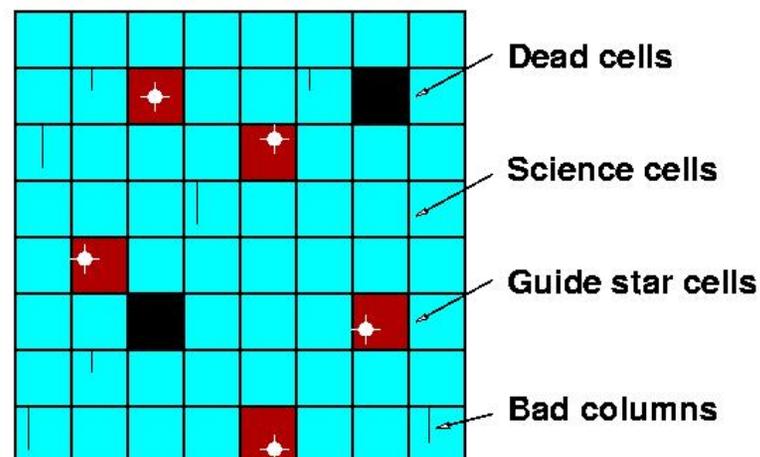
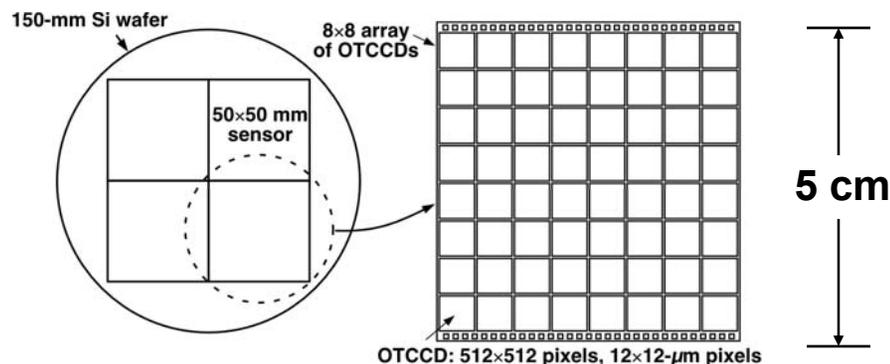




# Detector Details – Overview

## Each CCD cell of a $4K \times 4K$ OTA

- **Independent  $512 \times 512$  CCD**
  - Individual or collective addressing
  - 1 arcmin field of view
- **Dead cells excised, yield  $>50\%$** 
  - Bad columns confined to cells
- **Cells with bright stars for guiding**
- **8 output channels per OTA**
  - Fast readout (8 amps, 2 sec)
- **Disadvantage – 0.1 mm gaps, but gaps and dead cells are dithered out anyway**





# Summary

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- **CCD technology can meet or is close to meeting LSST requirements**
- **Other features of interest require additional development**
  - **Blooming control**
  - **Electronic shutter**
  - **OTA**